

MODELLING AEOLIAN SAND TRANSPORT AND MORPHOLOGICAL DEVELOPMENT IN TWO BEACH NOURISHMENT AREAS

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ABSTRACT

The aeolian sand transport model SAFE and the air flow model HILL were applied to evaluate cross-shore changes at two nourished beaches and adjacent dunes and to identify the response of aeolian sand transport and morphology to several nourishment design parameters and fill characteristics. The main input of the model consisted of data on the sediment, tide and meteorological conditions, and of half-yearly measured characteristics of topography, vegetation and sand fences.

The cross-shore profiles generated by SAFE–HILL were compared to measured cross-shore profiles. The patterns of erosion and deposition, and the morphological development corresponded. In general, the rates of aeolian sand transport were overestimated.

The impact of parameters that are related to beach nourishment (namely grain size, adaptation length and beach topography) on profile development was evaluated. Grain size affected the aeolian sand transport rate to the foredunes, and therefore the morphology. Adaptation length, which is a measure of the distance over which sediment transport adapts to a new equilibrium condition, affected the topography of the beach in particular. The topography of a beach nourishment had limited impact on both aeolian sand transport rate and morphology. Copyright © 2000 John Wiley & Sons, Ltd.

KEY WORDS: aeolian sand transport; air flow; topography; beach nourishment; modelling; foredunes; The Netherlands

INTRODUCTION

Beach nourishment is the artificial supply of sediment to a coast. In a sandy coast, the sediment provides both a buffer against marine erosion (and therefore prevents dune erosion) and a wide beach for recreational purposes. A side-effect of beach nourishment is that the aeolian sediment transport rate can be altered, which can have geomorphological and ecological consequences. Such a change in the rate of sediment transport may be the result of, for example, a change in the availability of sediment or sediment characteristics, and the air flow over the new topography (Van der Wal, 1998a).

The impact of such factors on entrainment, transport and deposition of sand by wind has been studied. Examples are the wind and the turbulent characteristics of air flow (e.g. Butterfield, 1998; Wiggs, 1993), availability of sediment (Nickling and Davidson-Arnott, 1990), sediment characteristics (Bagnold, 1941), moisture conditions (Hotta *et al.*, 1984) and slope angle (Iversen and Rasmussen, 1994). However, research conditions did not specifically apply to beach nourishment areas, as previous studies were carried out on natural beaches, desert environments or under wind tunnel conditions. So far, there are no tools to evaluate the effects of beach nourishment on the rate of aeolian sand transport. A model that addresses the impact and interaction of multiple factors has to be applied in order to evaluate the changes in aeolian sand transport due to individual factors changed by beach nourishment. Examples of these models are reported by Chapman (1990), Stam (1997), Namikas and Sherman (1998) and Van Dijk *et al.* (1999). Most models have not been validated with field data, although some models incorporate components that are derived under field conditions. In addition, the models were not applied to beach nourishment areas. Models designed or applied

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to evaluate impacts of beach nourishment (e.g. Hansen and Byrnes, 1991) merely focus on maximizing beach longevity and minimizing storm impact, excluding any aeolian component.

This paper focuses on aeolian sand transport and cross-shore profile changes in beach nourishment areas. Data from two beach nourishment areas along the Dutch North Sea coast (Figure 1) were used as an input for the aeolian sediment transport model SAFE of Van Dijk *et al.* (1999), which is dynamically linked to the air flow model HILL of Van Boxel *et al.* (1999). The models were applied to evaluate the aeolian sand transport and cross-shore profile changes at the two sites on a time scale of months. In addition, the models were used to identify the response of aeolian sand transport and morphology to parameters that are influenced by fill material and nourishment design, namely grain size, adaptation length (which is a measure of the distance over which sediment transport adapts to a new equilibrium condition, and which is assumed to depend on surface conditions) and topography. The performance of the models is discussed and suggestions for refinement are given to meet the needs of model application in beach nourishment environments on a time scale of months.

DESCRIPTION OF THE MODELS

In this section, a brief overview of the computer simulation models HILL and SAFE is given. Specifications of the models and the incorporated relationships taken from the literature are given by Van Boxel *et al.* (1999) and Van Dijk *et al.* (1999).

HILL is a two-dimensional second-order closure model by Van Boxel *et al.* (1999), based on the model of Zeman and Jensen (1987). The model simulates air flow and turbulence across linear ridges, using forward integration along streamlines. HILL calculates friction velocity along a topographic profile, using a given undisturbed (reference) friction velocity and a profile with roughness data created by SAFE, and returns the results to SAFE. In the case of a bare surface, HILL yields a surface friction velocity. Over a vegetated surface, model output relates to the friction velocity immediately above the vegetation cover.

The aeolian sand transport model SAFE has been developed by Van Dijk *et al.* (1999). It uses established relationships to calculate sand transport along the height profile and calculates resulting surface height changes, which are converted to new height profiles. Aeolian sand transport basically depends on threshold friction velocity and surface friction velocity. In SAFE, local threshold friction velocity depends on the mean grain diameter of the sand (Bagnold, 1941), local slope angle (Iversen and Rasmussen, 1994), rainfall and relative humidity of the air (Arens, 1996). Roughness characteristics are calculated from the aerodynamic roughness length of the sandy surface, and local vegetation characteristics (vegetation height and cover along the profile, and stem diameter of the plants) using a formula of Hagen and Armbrust (1994). A profile with roughness data is exported to HILL, which calculates friction velocities along the profile. From the friction velocities, SAFE calculates effective surface friction velocities, which incorporate vegetation effects (Raupach, 1992; Hagen and Armbrust, 1994). These values are used to calculate aeolian sand transport, using the transport formula of Kawamura (1951), with a transport constant of 2.61, as proposed by White (1979).

In SAFE, the upwind edge of sediment transport is the water line, which is calculated dynamically; water level is described by a sine-shaped curve with a 12 h periodicity and an amplitude of half the tidal range. The mean sea level (0 m + Dutch Ordnance Datum (DOD)) was set as deflation limit, to account for sea water moisture during low tide. An adaptation length, relating to the distance over which sediment transport adapts to a new equilibrium condition, according to a negatively exponential curve, is incorporated both for increasing and decreasing sediment transport in a downwind direction (Van Dijk *et al.*, 1999). The new condition is associated with a change in surface and vegetation characteristics or wind velocity, for instance. A similar concept has been used by Butterfield (1991) and Anderson (1988). The values used in SAFE are 20 m for increasing transport and 3 m for decreasing transport.

Additionally, a slip face routine is implemented. Sand is redistributed on leeward and windward slopes exceeding an angle of yield of 37° until an angle of repose of 34° is reached (Van Dijk *et al.*, 1999). On steep slopes, flow separation occurs (Oke, 1987). HILL cannot deal with the recirculation vortex resulting from this flow separation (Van Boxel *et al.*, 1999). Instead, SAFE accounts for these processes in a simple way. If a

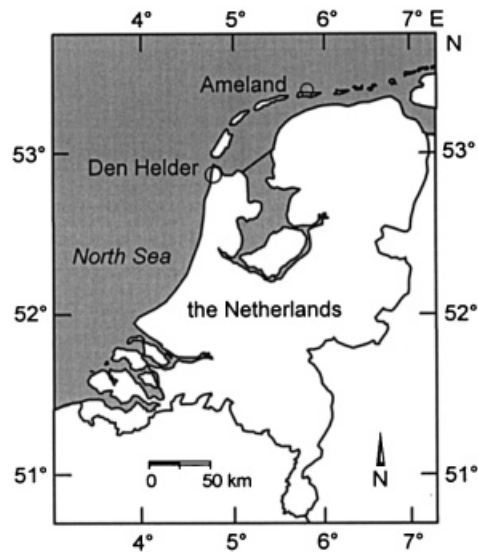


Figure 1. The study areas Ameland and Den Helder in The Netherlands

leeward slope exceeds 15° , a downwind zone is defined, in which friction velocities are 20 per cent of the reference friction velocity (Van Dijk *et al.*, 1999).

Input for SAFE and HILL include timing information (namely time step interval and run duration) and a specification of the grid node spacing. SAFE and HILL interact dynamically. HILL is activated whenever a given change in height along the profile is exceeded. The output of HILL is then used as input for SAFE, and vice versa.

For this study, the models are adapted to meet the requirements of the sites to be simulated. For example, procedures to simulate the effect of sand fences are added. The effect of sand fences on the wind flow is calculated in HILL (using position, height and porosity of the fences), since the sand fences extract momentum from the air (Wilson and Shaw, 1977). SAFE adjusts the fence height after deposition or erosion and passes the new fence characteristics to HILL.

APPLICATION OF THE MODELS

Study sites

The study was conducted on two sites along the Dutch North Sea coast (Fig. 1). The study site referred to as Ameland is situated on the North Sea side of the barrier island of Ameland, near the village of Ballum. The aspect of the coast is 0° . The beach was nourished in the spring and summer of 1996, with 1.2 Mm^3 of sand deposited along a stretch of coast of 4 km. The study area referred to as Den Helder is situated on the coast of North-Holland, about 3 km from the town of Den Helder. The aspect of the coast is 272° . A first nourishment was carried out between the summers of 1992 and 1993. A second beach nourishment was carried out in the summer of 1996, when about 0.85 Mm^3 of sand was placed along a stretch of coast of approximately 5 km. Most of the 1996 nourishment sand was deposited on the foreshore.

Model input

Time series

Data have been collected at approximately half-yearly intervals between the spring of 1996 and the autumn of 1997 at both locations. The data set of spring 1996 represented the situation just before nourishment. Three

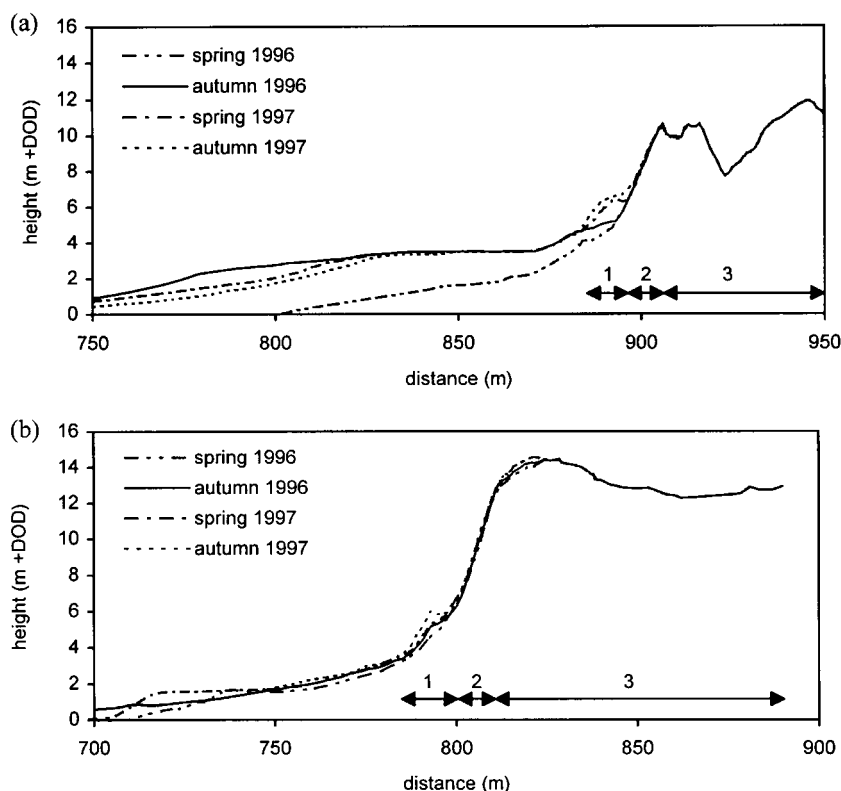


Figure 2. Measured topographical development for (a) Ameland and (b) Den Helder. The numbers refer to geomorphological zones: 1, dune toe; 2, seaward slope of the foredune; 3, foredune crest

sets of data were collected after nourishment (i.e. autumn 1996, spring 1997 and autumn 1997). Table I lists the exact data collection dates.

Topography

At the Ameland site, there is a vegetated foredune ridge of over 10 m + DOD adjacent to the beach, aligned parallel to the shore, and a second ridge more inland. The beach at the Den Helder site is bordered by a foredune of 14 m + DOD. The study sites were selected because of their two-dimensional character; shore-parallel variations in topography are small.

Table I. Data collection dates

Time series	Ameland		Den Helder	
	Topography	Vegetation and fence	Topography	Vegetation
Spring 1996	7 May 1996	5 May 1996	15 Jun 1996	16 Jun 1996
Autumn 1996	9 Oct 1996	10 Oct 1996	21 Dec 1996	12 Dec 1996
Spring 1997	9 May 1997	10 May 1997	13 Jun 1997	14 Jun 1997
Autumn 1997	18 Oct 1997	19 Oct 1997	8 Nov 1997	15 Nov 1997

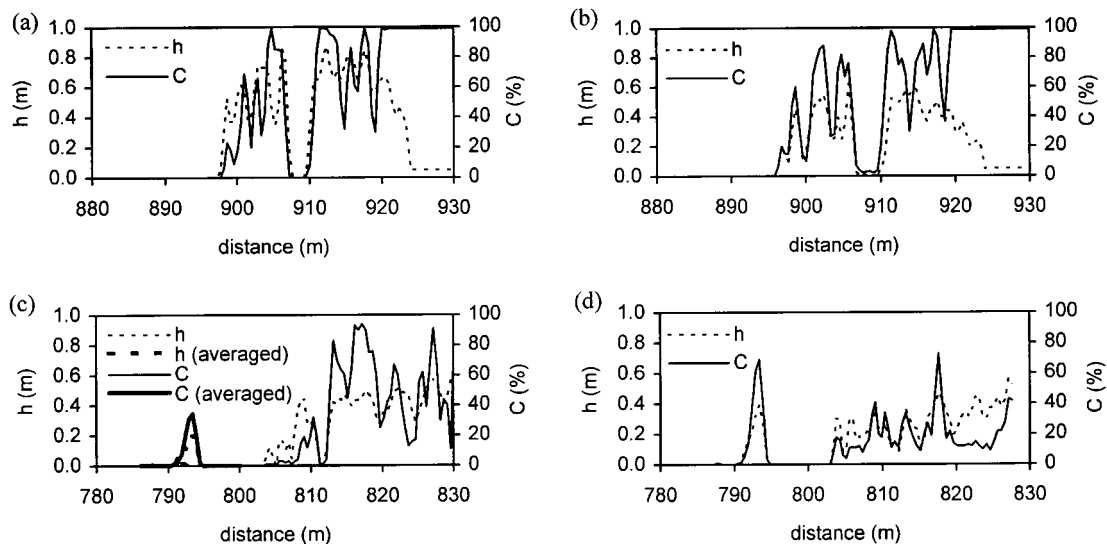


Figure 3. Cross-shore profile of vegetation height h and vegetation cover C at the Ameland site measured in (a) autumn 1996 and (b) spring 1997, and at the Den Helder site in (c) autumn 1996 and (d) spring 1997. The bold lines in (c) represent the average vegetation characteristics of autumn 1996 and spring 1997 used in SAFE-HILL to account for vegetation growth in the period between autumn 1996 and spring 1997

The models require cross-shore height profiles. Laser electronic distance measurement (EDM) equipment was used to measure the height along transects that were marked in the field. A transect that spanned the beach, the foredunes and the inner dunes was used for this study. The accuracy of EDM is better than 0.01 m in the vertical. Established benchmarks, of which the exact position was known, were also surveyed. They were used to express the heights in metres + DOD, which is about mean sea level. Distances along the transect were expressed relative to an arbitrary benchmark. Figure 2 gives the selected cross-shore profiles.

Vegetation

At the Ameland site, vegetation on the foredune consists of marram grass (*Ammophila arenaria*) and baltic marram grass (*Calammophila baltica*). The inner dunes are completely covered with mosses and sea buckthorn (*Hippophaë rhamnoides*). At the Den Helder site, the dune toe is dominated by the grass sand couch (*Elymus farctus*), and the foredunes and inner dunes are dominated by marram grass (*Ammophila arenaria*) and baltic marram grass (*Calammophila baltica*).

Vegetation input for SAFE-HILL mainly consists of cross-shore profiles with information on vegetation height and cover. Each EDM transect was divided in 0.10 m segments of 0.10 m in width. Mean vegetation height and cover (as seen from above) were recorded at half-yearly intervals in each 0.10 m by 0.10 m plot. Cross-shore profiles of vegetation height and cover were constructed by applying a moving average over 1 m intervals. Figure 3 shows the results.

For the Den Helder site, the height and cover of the grass sand couch at the dune toe changed considerably between the measurements of autumn 1996 and spring 1997, due to vegetation growth in May and June 1997. Dune toe vegetation of the autumn 1996 and spring 1997 data was therefore averaged and used for vegetation input for autumn 1996, to account for this growth in a simple way (Figure 3c).

Additional measurements were carried out on Ameland on 5 May 1996 and on the Den Helder site on 24 July 1996. The diameters of the individual marram grass shoots were determined in four plots of 0.10 m by 0.10 m along the mean transect, situated on the dune toe, the seaward slope of the foredune, the foredune crest and the inner dunes, respectively. An average shoot diameter of 3 mm was found for both sites, and used in SAFE-HILL.

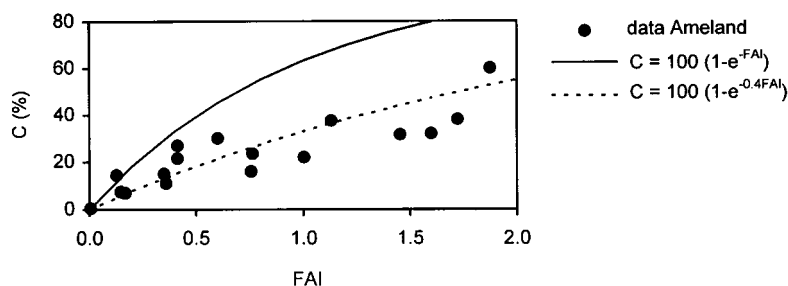


Figure 4. Frontal area index (FAI) versus vegetation cover C for the marram grass vegetation on the foredune of Ameland. The solid line represents the Raupach *et al.* (1993) equation. The dotted line represents the equation, based on field data from Ameland, which was used in this study

For SAFE, frontal area index (which is the multiplication of the number of plants per unit surface area, the plant diameter and the vegetation height) values are required. The values can be obtained from vegetation height and cover by an equation mentioned in Raupach *et al.* (1993), assuming that the vegetation can be represented by uniformly distributed standing stalks. The height and cover of marram grass and the number of shoots were measured on plots of 1 m by 1 m along the main transect of the Ameland site on 13 April 1998. The conversion equation of Raupach *et al.* (1993) was adapted based on these field data (Figure 4).

Sand fences

The characteristics of sand fences have to be specified in the models. On the Ameland site, a sand fence was present before nourishment (spring 1996), and buried during nourishment. A new fence, consisting of reeds, was erected just after completion of the data collection of autumn 1996. Another fence was erected seaward of this fence (between spring and autumn 1997), when the fence was almost buried. The position of the sand fence and the mean fence height were noted at half-yearly intervals for every fence along the transect (Table II). The porosity of the fences was 36 per cent.

Sediment characteristics

SAFE uses mean grain size of the sand to characterize the sediment. Therefore, the surface of the beach was sampled (Van der Wal, 1998b). The native beach on Ameland (spring 1996) was composed of sand with a mean grain diameter of 0.202 mm. After nourishment (autumn 1996 to autumn 1997), the Ameland site had complex sediment characteristics due to shell lag development on the supratidal beach. The mean grain size of the surface sand was 0.323 mm.

Sand that was sampled prior to the 1996 nourishment on Den Helder (spring 1996) was composed of sand with a mean diameter of 0.332 mm. After the 1996 nourishment (autumn 1996 to autumn 1997), the (moderately well sorted) surface sand had a mean grain size of 0.272 mm. Both before and after the 1996 nourishment, the sand contained some shell fragments.

Table II. Characteristics of sand fences at the Ameland site

Time series	Fence	Position (m)	Height (m)
Spring 1996	1	881.55– 881.74	0.50
Autumn 1996	2	887.25– 887.44	0.80
Spring 1997	2	887.25– 887.44	0.42
	3	884.40– 884.59	0.80
Autumn 1997	3	884.40– 884.59	0.70

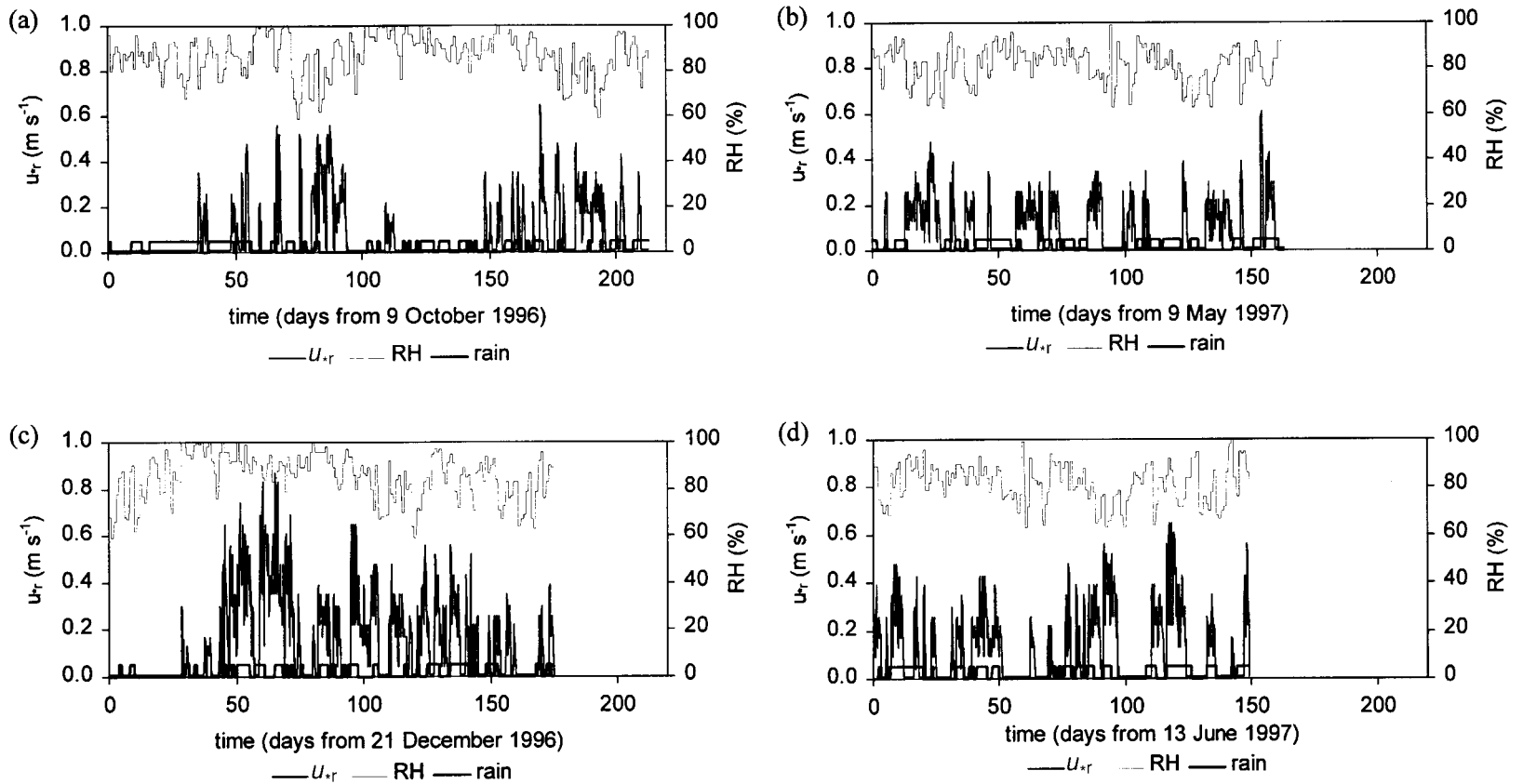


Figure 5. Reference friction velocity u_{*r} , relative humidity (RH) and rain for Ameland for (a) autumn 1996 to spring 1997 and (b) spring 1997 to autumn 1997, and for Den Helder for (c) autumn 1996 to spring 1997 and (d) spring 1997 to autumn 1997. Friction velocities during onshore winds are displayed; friction velocities during offshore and shore-parallel winds are set to 0.01 m s^{-1} . Rain is displayed as a boolean, with 'no rain' values set to 0

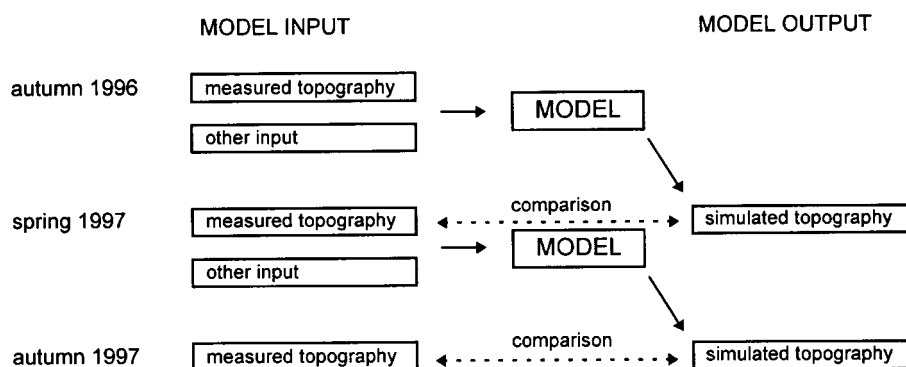


Figure 6. Schematic representation of model evaluation

Tidal characteristics

The Ameland site has a semi-diurnal tide with a mean tidal range of about 2.0 m (meso-tidal). The tide at the Den Helder site is semi-diurnal and the mean tidal range is 1.4 m (micro-tidal).

Meteorological conditions

The meteorological conditions to be specified in SAFE-HILL were obtained from weekly published reports of the Royal Netherlands Meteorological Institute (1996, 1997), providing daily data. Meteorological station De Kooij is about 3 km from the Den Helder site, but also provides reasonable data for the Ameland site, since it is representative for the Dutch North Sea coast (Wieringa and Rijkoort, 1983).

The average and maximum wind velocities, averaged per day, were used. A reference wind velocity was generated for every 3 h, by fitting a sine-shaped curve through the average and maximum daily wind velocity values. In this manner, the range of wind velocities occurring during each day was represented. Subsequently, the reference wind velocities were converted to reference friction velocities, using the logarithmic wind profile equation (e.g. Oke, 1987), assuming a fixed aerodynamic roughness length of 0.001 m for bare sand. Average relative humidity of the air was also used. Precipitation data were used to distinguish between days without rain (i.e. day total of less than 0.05 mm) and days with rain.

SAFE-HILL only applies to onshore winds. Therefore, wind direction data (from meteorological station De Bilt) were used to distinguish between onshore, shore-parallel and offshore winds. Days with onshore winds had winds with a westerly component (SW, W and NW) for the Den Helder site and winds with a northerly component (NW, N and NE) for the Ameland site. Days with shore-parallel winds and offshore winds, occurring for 50 to 70 per cent of the observed period, were discarded. Figure 5 lists the meteorological conditions for selected periods.

Model evaluation

Measured and simulated aeolian sand transport and morphological development

The topographic profiles generated by the model system were related to measured topographic profiles for two data series, as represented in Figure 6. The pattern of deposition and erosion reflected in the topographical development, and volumetric changes are compared. The profiles measured in spring 1996 cannot be used, since the development due to aeolian processes is obscured by the direct impact of nourishment.

Simulated aeolian sand transport and morphological development for several cases

A number of cases were simulated to identify the response of aeolian sand transport and morphology to parameters that can be influenced by beach nourishment. Simulation runs with different values for grain size

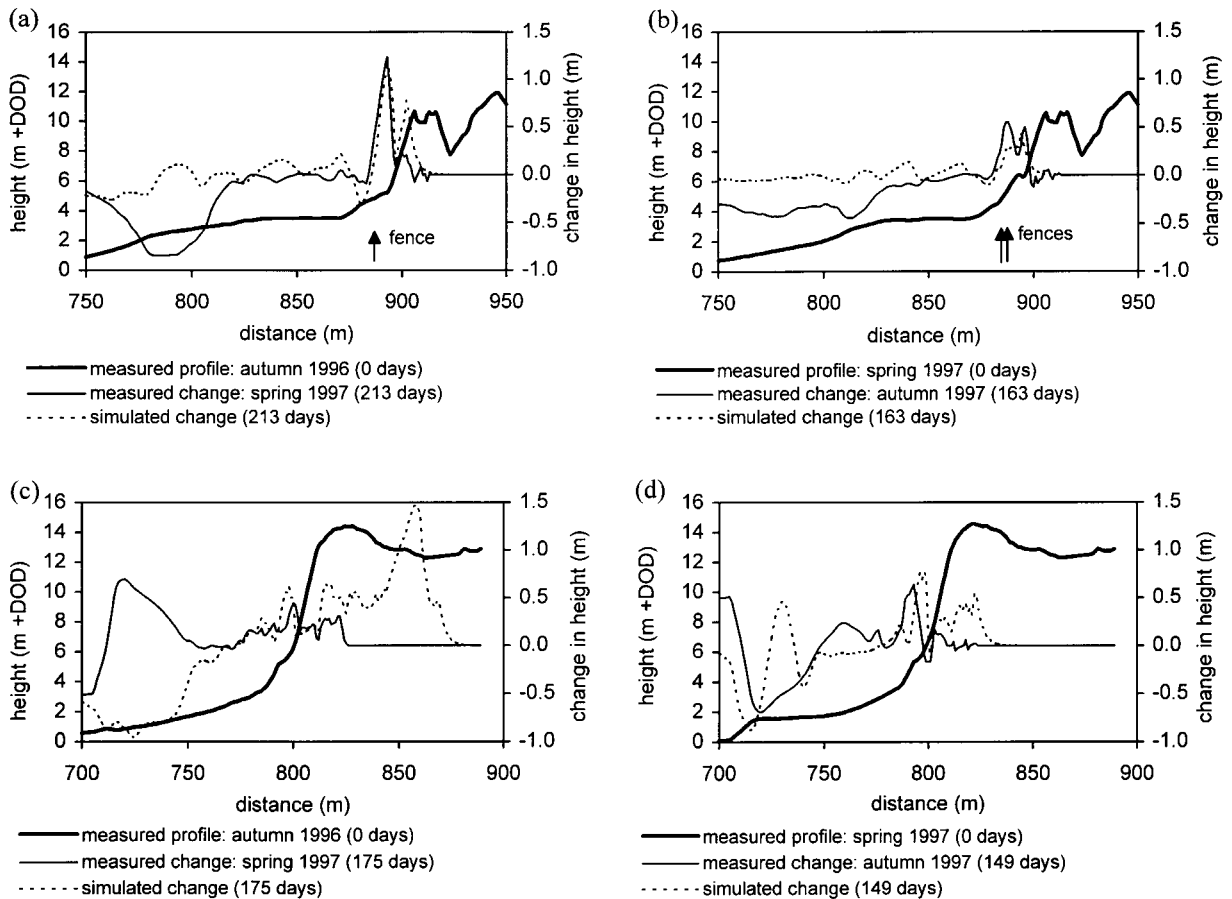


Figure 7. Measured and simulated profile development on the Ameland site for the periods (a) autumn 1996 to spring 1997 and (b) spring 1997 to autumn 1997, and on the Den Helder site for the periods (c) autumn 1996 to spring 1997 and (d) spring 1997 to autumn 1997

(e.g. the grain size of the pre-nourishment sand and the nourishment sand) and for adaptation length (for increasing sand transport in a downwind direction), which is assumed to depend on surface conditions (e.g. Davidson-Arnott and Law, 1990), were evaluated to illustrate the effect of fill material. Simulations with a pre-nourishment profile, a post-nourishment profile and two beach fill design template geometries were run to assess the effect of topography on aeolian sand transport and morphology. The data collected in autumn 1996 at the Ameland site were used for these cases. Both a reference friction velocity of $u_{*r} = 0.35 \text{ m s}^{-1}$ during 20 days and the meteorological input during 213 days (i.e. the number of days between the autumn 1996 and spring 1997 series) were applied. For all runs, a time step interval of 0.005 days and a grid node spacing of 1 m were selected.

RESULTS

Measured and simulated aeolian sand transport and morphological development

Figure 7a gives the simulated profile development for the autumn 1996 to spring 1997 period at the Ameland site. Both the actual and simulated situation show largest deposition just behind the sand fence. The simulated sand influx at the seaward slope of the foredune is overestimated. The simulation shows dune

Table III. Measured and simulated net deposition ($\text{m}^3 \text{m}^{-1}$) at the dune toe, the seaward slope of the foredune and the foredune crest at the Ameland and Den Helder site.

Time series	Ameland			Den Helder		
	Dune toe	Seaward slope	Crest	Dune toe	Seaward slope	Crest
Autumn 1996 to spring 1997						
Measured	7.38	1.34	-0.03	3.17	2.37	3.12
Simulated	7.07	4.60	0.76	4.90	1.77	40.82
Spring 1997 to autumn 1997						
Measured	5.13	-0.29	0.06	4.37	0.43	0.00
Simulated	3.62	0.26	0.03	5.53	2.02	6.18

development due to convexities in the beach profile: the convex slopes propagate and grow higher. The simulated change for the period spring to autumn 1997 (Figure 7b) corresponds well with the actual change, but the sand influx is slightly underestimated.

At the Den Helder site, equal amounts of sand were trapped at the dune toe and the foredune crest in the period autumn 1996 to spring 1997 (Figure 7c). The simulation shows extreme deposition at the foredune crest. This is the result of a period of strong winds (occurring between 51 and 71 days after the start of simulation, as can be seen in Figure 5c). During the subsequent period with lower friction velocities, the accumulated sand migrates downwind. In the period spring to autumn 1997, almost all sand was trapped at the dune toe (Figure 7d). The simulated distribution of deposition at the dune toe and foredune crest does not correspond with this measured distribution. Again, the rates are overestimated. The swashbar that was measured in spring 1997 develops similarly as the convexities in the beach profile of the Ameland site.

Table III summarizes volumetric changes for three geomorphological zones, calculated from the measured and simulated profiles of the Ameland and Den Helder site. Simulated net deposition is 0.8 to 1.4 times the measured net deposition on the Ameland site, and 2.9 to 5.5 times the measured net deposition on the Den Helder site.

The data set of autumn 1996 of the Den Helder site was also used to simulate 5 days of profile development with several friction velocities (Figure 8). The simulations show that the trap efficiency of the dune toe depends both on vegetation characteristics and on friction velocity. A denser and higher dune toe vegetation leads to more deposition at the dune toe. In addition, deposition at the dune toe is bound to a maximum. With higher friction velocities, more sand is deposited on the foredune crest, as compared to the dune toe, and the sand is transported further landward.

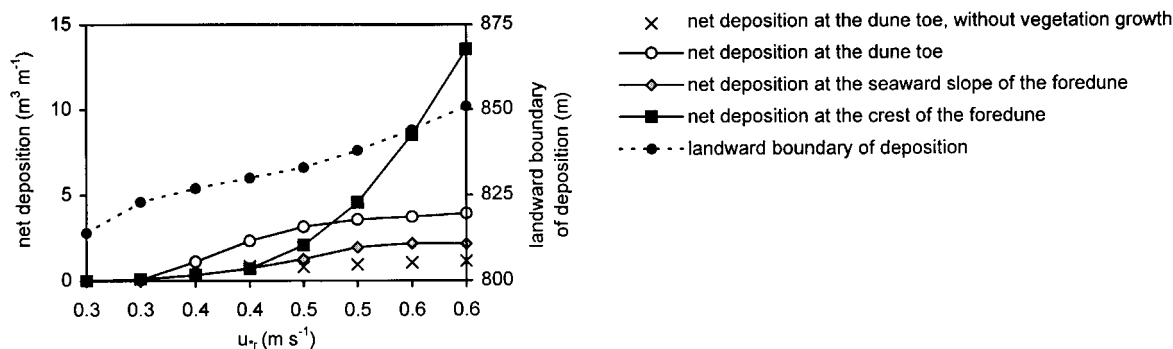


Figure 8. Simulated net deposition in the geomorphological zones indicated in Figure 2b, and landward boundary of deposition for simulation runs of 5 days with different reference friction velocities u_{*t} , using Den Helder input from autumn 1996. Except for the first data series, input of dune toe vegetation consisted of averaged data of autumn 1996 and spring 1997, to account for vegetation growth (see also Figure 3c)

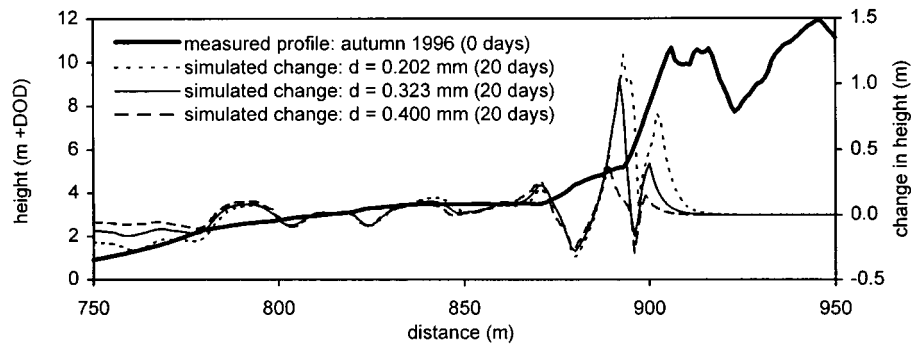


Figure 9. Effect of grain size on profile development. The model simulated 20 days of profile development, with a reference friction velocity of 0.35 m s^{-1} and a sediment grain size d of 0.202 (pre-nourishment sand), 0.323 (nourishment sand) and 0.400 mm

Simulated aeolian sand transport and morphological development for several cases

Several cases were simulated to assess the effect of grain size, adaptation length and topography. Figure 9 and Table IV show the effect of grain diameter on aeolian sand transport and cross-shore profile changes during a simulation run of 20 days with $u_{*r} = 0.35 \text{ m s}^{-1}$. The rates of sand transport, and thus the morphological stage after 20 days, decrease with increasing grain size. The same patterns are revealed for runs with input of the meteorological data set for the period autumn 1996 to spring 1997, although transport rates are higher. The effect of a difference in grain size before and after the Ameland beach nourishment would be to reduce the influx to the dunes by about 50 per cent in this period (Table IV). When the aeolian sand transport rates are very high, the trap efficiency of the sand fence decreases due to burial, and the deposition zone behind the fence changes to a transport zone, over which sand is transported into the foredunes.

Table IV. Simulated net deposition ($\text{m}^3 \text{ m}^{-1}$) at the dune toe, seaward slope of the foredune and foredune crest on the Ameland site for several cases, both for a variable wind regime for the period autumn 1996 to spring 1997 and for a fixed reference friction velocity (u_{*r}) of 0.35 m s^{-1} for 20 days of simulation

	u_{*r} variable, 213 days			$u_{*r} = 0.35 \text{ m s}^{-1}$, 20 days		
	Dune toe	Seaward slope	Crest	Dune toe	Seaward slope	Crest
Grain size						
$d = 0.202 \text{ mm}$	7.84	5.61	4.65	6.94	4.73	0.81
$d = 0.323 \text{ mm}$	7.07	4.60	0.76	4.49	1.65	0.16
$d = 0.400 \text{ mm}$	6.52	2.76	0.30	1.47	0.31	0.04
Adaptation length for increasing sand transport						
$\chi = 10 \text{ m}$	8.22	4.59	1.00	5.09	2.06	0.36
$\chi = 20 \text{ m}$	7.07	4.60	0.76	4.49	1.65	0.16
$\chi = 50 \text{ m}$	6.15	4.37	0.69	3.97	1.28	0.10
Topography						
Pre-nourishment beach	—	—	—	1.83	4.35	1.11
1996 beach nourishment	—	—	—	2.05	3.87	0.61
Beach nourishment	—	—	—	1.39	4.26	1.08
Beach nourishment and banquet	—	—	—	7.33	2.77	0.38

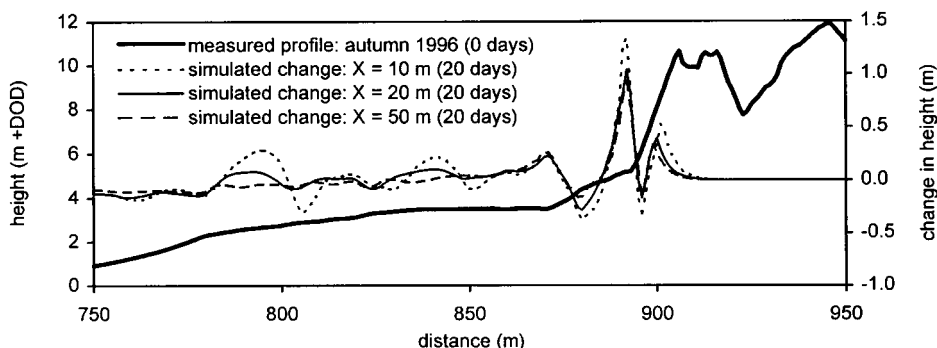


Figure 10. Effect of adaptation length (of increasing sand transport with distance downwind) on profile development. The model simulated 20 days of profile development, with a reference friction velocity of 0.35 m s^{-1} and an adaptation length for increasing sand transport χ of 10, 20 and 50 m

The effect of adaptation length is presented in Figure 10 and Table IV. Larger values for the adaptation length cause smoother transport gradients and therefore a smoother topography, with less developed microdunes on the beach. Adaptation length has no pronounced effect on the morphological development of the dune toe and foredune, although the rates of aeolian sand transport to the foredunes are slightly suppressed by an increase in adaptation length.

Figure 11 shows the effect of topography on aeolian sand transport and morphology, after 20 days of simulation with $u_{*r} = 0.35 \text{ m s}^{-1}$. Note that no sand fence was applied for these runs. The ridge at the dune toe of the pre-nourishment profile, formed by a former sand fence, will erode and the sand will eventually be transported over the seaward slope of the foredune, to increase the foredune crest by 0.7 m (Figure 11a). In the profile of the 1996 beach nourishment (Figure 11b), there is some redistribution of sand on the beach and at the dune toe. Sand is deposited at the dune toe and the seaward slope of the foredune, rather than on the foredune crest. The development with beach nourishment and with a 1:50 slope (Figure 11c) approaches the development without nourishment. A combination of beach nourishment and a so-called banquet, i.e. a sand buffer at the dune toe (Figure 11d), results in less growth of the foredune crest, but there is a dramatic adaptation of the banquet shape. Differences in total net deposition landward of the dune toe between the profiles were small (Table IV). The largest total net deposition was found for the profile without nourishment. The total rates of the profile with both beach nourishment and a banquet were also high. This is because the erosion at the banquet, situated seaward of the dune toe, was not taken into account.

DISCUSSION

Measured and simulated aeolian sand transport and morphological development

Aeolian processes in two beach nourishment areas can be simulated using SAFE-HILL. The model system indicates the location of deposition and erosion. The sand fence dramatically affects the morphology on the Ameland site; most sand was trapped behind the fence. At the Den Helder site, sand is deposited at the dune toe and crest. The morphological development is defined by the vegetation at the dune toe and by the wind velocity, which determines the landward boundary of deposition.

In general, the rates of sand transport simulated by the model system are overestimated compared to the rates of sand transport in the field. This corresponds with the findings of most authors who used sediment transport equations and meteorological data to predict volumes of sediment transported from the beach to the dunes, and compared this with measured accumulation (e.g. Sarre, 1989; Davidson-Arnott and Law, 1990; Kroon and Hoekstra, 1990; Arens, 1997). The overestimation can be explained by the fact that a number of factors that reduce aeolian sand transport are not well accounted for.

For these sites, soil moisture is probably the most important factor. Empirically and theoretically derived equations to predict the effect of moisture content on aeolian sand transport give a wide range of outcomes

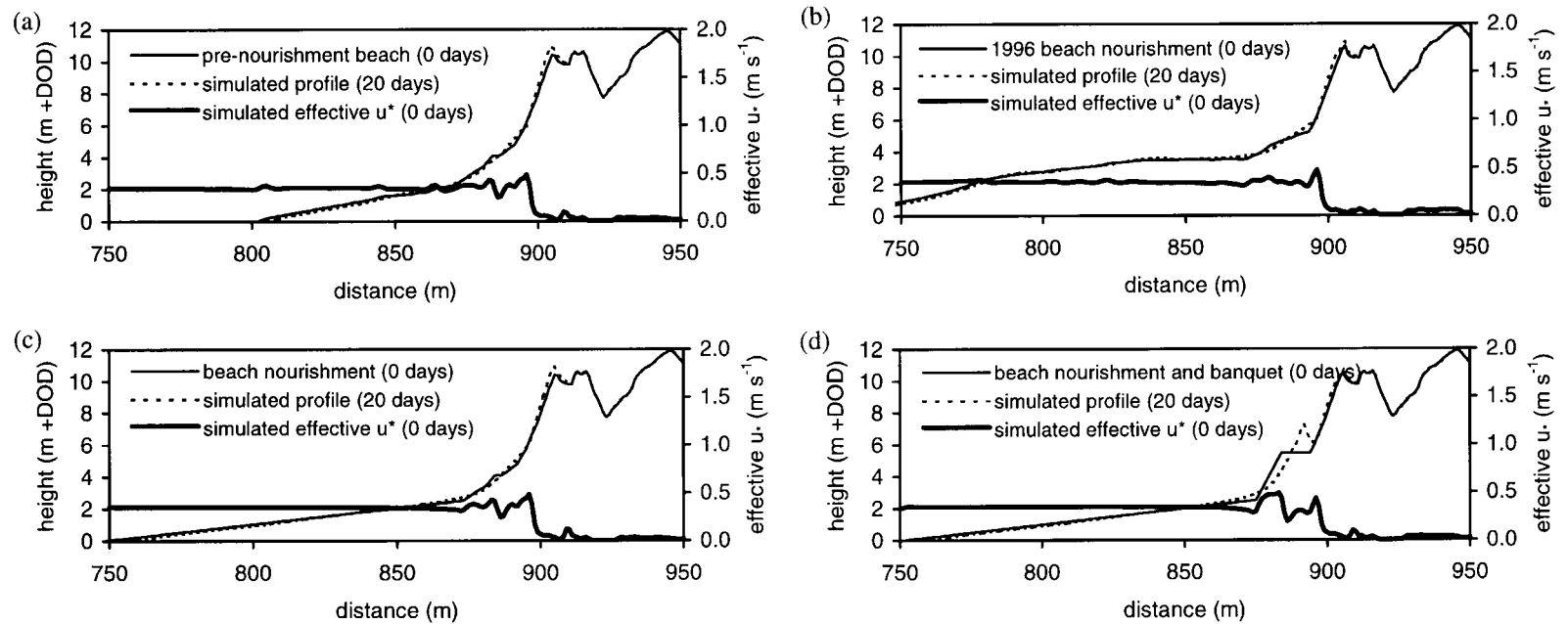


Figure 11. Effect of topography on aeolian sand transport and foredune morphodynamics. The models simulated 20 days of profile development, with a reference friction velocity of 0.35 m s^{-1} , for four different initial profiles: (a) the topography of spring 1996 ('pre-nourishment beach'); (b) the topography of autumn 1996 ('1996 beach nourishment'); (c) a template geometry, with beach fill under $2.5 \text{ m} + \text{DOD}$, sloping 1:50 ('beach nourishment'); (d) a template geometry, with a so-called banquet of $5.45 \text{ m} + \text{DOD}$, 10 m in width and sloping 1:3, superimposed on the previous template ('beach nourishment and banquet'). Simulated values for the initial effective friction velocities are also displayed

(Namikas and Sherman, 1995). In SAFE, moisture is empirically related to threshold friction velocity by relative humidity and by rain. Wetting of the beach by sea water is incorporated in SAFE by setting a deflation limit to mean sea level. The model instantaneously reacts to changes in conditions. The field situation is more complex. Moisture content is highly variable in both time and space. There is no instantaneous reaction to changes in conditions; the effect of rain on threshold friction velocity, for instance, does not cease directly after the rain has stopped. In addition, a wet surface can both restrict the supply of sand to the air stream and form a good surface for transport of sand. Furthermore, high wind speeds are relatively unimportant, because of their occurrence in combination with rainfall and flooding of the beach by sea water. Further research should focus on the effects of moisture on aeolian sand transport under field conditions.

Part of the overestimation of sand transport will be due to the unidirectionally modelled wind. Days with shore-parallel and offshore winds were discarded. This is justified, since velocities of offshore winds are lower, and the beach and dune toe are in the lee of the dunes during offshore winds. Sand transport during onshore winds leads to changes in the topography in particular, since the transported sand can be stabilized either behind a sand fence or within the vegetation. Discarding the parallel winds with an onshore component reduced the aeolian sand transport. The model system does not differentiate between days with oblique onshore winds and days with perpendicular onshore winds. In the field, oblique winds encounter slopes that are less steep. This results in less acceleration and deceleration of the air flow, and therefore in smoother transport gradients. The effect of a reduction of threshold friction velocity due to the decrease in slope angle is less pronounced. Deflection of the wind due to the presence of the foredune has to be taken into account when the wind direction strongly deviates from perpendicular onshore. In addition, sediment input per unit distance alongshore decreases as the wind angle departs from shore-perpendicular (Nickling and Davidson-Arnott, 1990). Additional simulations with the current model system, in which a module is implemented that accounts for these effects of wind direction, results in a more accurate prediction of morphological changes in the foredunes, but also intensifies dune-building on the beach, since the fetch of wind over sand is enlarged during oblique winds.

The model system has been designed to simulate aeolian sand transport on a time scale of several wind erosion events. The model performance on a time scale of months depends on the variability of factors that are not dynamically modelled, especially seasonal variation in vegetation and marine sediment transport. At the Ameland site, differences in vegetation height and cover were insignificant (Figure 3a and b). In addition, the bulk of the sediment is deposited in the bare zone behind the sand fence. At the Den Helder site, vegetation growth at the dune toe controls dune development. Since the model system lacks any vegetation growth function, deposition zones change to transport zones once the vegetation is buried, thus moderating the morphological development. Especially at the dune toe on the Den Helder site, simulation therefore fails. For the situation in which vegetation is crucial for morphological development, seasonal variation in vegetation characteristics has to be included in the model system. In addition, the geometry and distribution of plants have to be taken into account in more detail in this situation.

The model system generates micro-dunes on the beach. This occurs especially where the concave slope of the beach face, which is mainly under the influence of marine processes, changes to a more convex slope, which is under the influence of aeolian processes only. The dunes did not form on (sloping) flat beaches, such as in Figure 11a, c and d. The migration and growth of the micro-dunes is comparable to the development of the non-vegetated sinus-shaped dunes simulated by Van Dijk *et al.* (1999). In reality, these dunes did not form on the beach. This discrepancy can be attributed to processes acting on the beach that are not included in the model system, or not modelled correctly, but are also likely to result from model artefacts. Wave and tidal processes control beach development (see, for example, the marine erosion in Figure 2a and the swashbar formed in the spring profiles in Figure 2b), but are not included in the model system. In addition, values for threshold friction velocity and adaptation length, for example, may not be chosen properly. Finally, the individual factors that determine aeolian sand transport may not be well balanced in the model system. There is, for instance, a distinct response of friction velocity to small irregularities in topography in the model system.

Simulated aeolian sand transport and morphological development for several cases

The model system is able to identify the impact of artificial beach nourishment, since the models incorporate variables that are changed by nourishment. The effects of grain size, adaptation length for increasing sand transport, and topography were evaluated. Grain diameter acts in SAFE to change the threshold friction velocity. SAFE assumes well sorted, cohesionless sand. It does not include a (gradual) transition of the sand characteristics due to selection processes. Nourishment sand, however, is often only moderately sorted, and may contain silt, shell fragments and gravel (Van der Wal, 1998a). The model system can be refined by adding procedures that consider the effect of such factors.

The model system is sensitive to the value of adaptation length. Larger values for the adaptation length cause smoother transport gradients and therefore a smoother topography, which corresponds more closely to the actual topography. SAFE uses an adaptation length of 20 m for increasing sand transport by default. Most wind tunnel studies (Kawamura, 1951; Butterfield, 1998) and model studies (McEwan and Willetts, 1993) give smaller values, whereas most field studies (Stout, 1990; Fryrear *et al.*, 1991) report larger values. Field observations indicate that surface conditions strongly affect the adaptation length, as far as they determine sediment supply (Davidson-Arnott and Law, 1990; Arens, 1996; Van der Wal, 1998b). Moisture content and lag deposits (of shells or gravel, for instance) can increase the adaptation length. It is important to quantify the value of adaptation length for different surfaces and conditions. The fetch of onshore winds over beach sand, depending on tide and beach topography, may be critical. The sine-shaped tidal curve now used in SAFE could be replaced by tidal observations. The decrease in beach width after beach nourishment has to be simulated by coupling the model system to a model that simulates beach profile response to storm waves and water level, such as SBEACH (Hansen and Byrnes, 1991) or DUROSTA (Steetzel, 1993).

When dealing with the impact of topography on aeolian sand transport and morphology, SAFE-HILL simulates the effects of topography on the pattern of acceleration and deceleration of the air flow over the dune, and also on the threshold friction velocity through slope angle. The coupling of an air flow model and a sediment transport model therefore demonstrates the mere impact of nourishment design on aeolian sand transport. Other potential effects of topography, such as effects of moisture conditions due to a raised beach level, are not taken into account in the model system.

CONCLUSIONS

The aeolian sand transport model SAFE and the air flow model HILL were applied to simulate aeolian sand transport and morphological development in beach nourishment environments on a time scale of months. The model system qualitatively explained cross-shore profile development due to aeolian processes. It gave a good indication of erosion and deposition. The simulated morphological development corresponded with the measurements at the study sites. On a time scale of months, quantification of the volume changes remains to be improved. In general, the rates of transport were overestimated, since a number of factors that reduce aeolian sand transport are not well accounted for.

With these benefits and limitations of the model system in mind, the impact of beach nourishment parameters on profile development can be evaluated. The grain size of the nourishment affected the rate of aeolian sand transport and therefore the morphology of the dune area. The adaptation length for increasing sand transport especially affected the beach topography. Different nourishment designs, especially beach nourishment versus a so-called banquet, resulted in different morphological development.

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